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A FRAMEWORK FOR INFORMATION TECHNOLOGY INTEGRATION IN PROCESS PLANT AND RELATED INDUSTRIES

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Abstract

The benefits of developing re-usable, integrated data during the design and construction of process plants have been difficult to quantify and achieve. Although Engineering and Construction (E&C) firms are generally willing to develop such data and owner/operators are receptive to the benefits of re-usable data, the clear justification of the additional costs and process changes needed to use such added value information has proved difficult. The main problem lies in assessing the impact of re-usable information on the support of the entire plant life cycle.

This problem is solved by introducing a **constraint framework** capable of capturing all requirements placed on the plant during its life cycle. The root constraints on the process plant are attributed to the business case, external and agent-specific constraints applied to the plant constructed during its entire life cycle. The **business case** includes processes that produce the plant, such as work performed by E&C firms. In most cases, when concurrent and downstream (during a later phase) constraints are addressed early during E&C work, costs are avoided in later work. Many of these constraints call for data elements, relationships, and work processes that are similar to or derived from those produced during earlier E&C work processes.

Functional models based on satisfying constraints in this framework can be evaluated for the contribution of each function to a root constraint. Deliveries of data between functions is due to the cost/beneficial need to support surrounding functions, independent of any phase of the work. A comparison is made to prior characterization of process plant design based on **project phases**. Phased models place too much emphasis on contractual boundaries largely defined by tasks primarily associated with a single state of the plant (e.g., a first cost estimate performed during preliminary design). Functional models based on phased work processes overlook the similarities between functions in successive phases and the evolutionary nature of the data they produce and use. Less thought is given to the needs of downstream users of data, and results in

evolutionary nature of the data they produce and use. Less thought is given to the needs of downstream users of data, and results in deliverables that are constrained by explicit items in the current phase's Statement of Work (**SOW**). The framework should lead to improved functional models which can effectively address root constraints at every stage of the plant life cycle, including design.

We verify that the framework still leads to familiar E&C and operational functions by a brief Integrated Definition Method 0 (**IDEF0**) diagram refined from the root constraints. We also demonstrate that external constraints applicable to plant operations apply to E&C work by a direct analysis of real Occupational Safety and Health Administration (**OSHA**) Process Safety Management (**PSM**) regulatory and citation language.

We apply this framework to the business case for 3D modeling (qualitatively) and to digital delivery of Piping and Instrumentation Drawings (**P&ID**) from design engineers to owner/operators for Computer-Aided Design/Drafting (**CAD**) updating. If updates are made to single-source P&IDs (i.e., a common database) and quickly reissued, estimates of $900 in non-value-added work (e.g., rechecking suspect data and reconciling multiple authoritative source documents) is eliminated. This estimate neglects beneficial support of other concurrent and downstream processes, including materials acquisition and Process Hazards Analysis (**PHA**).

A research agenda is proposed to enhance the application of framework concepts throughout the E&C industry. It is also recommended that owner/operators lead in identifying life-cycle constraints and address them in internal and subcontracted processes and revised contract language used with external agents.

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A Framework for Information Technology Integration in Process Plant and Related Industries

1. Introduction

The Process Plant and related industries have adopted several automation technologies, i.e., CAD, CAM, CAE with mixed success. Although process plant design is comparable to the electrical/electronics design, which also:

- designs and fabricates technologies that are abstractly similar as distribution systems (i.e., current and chemicals, both flow),
- uses highly tiered systems of component suppliers, designers, fabricators and owners,

its level of efficiency remains low. Where the electronics industry becomes more and more integrated, process plant designers and operators have chosen to minimize labor costs. This logically concludes that owners preferred to design, build, and operate plants overseas where labor rates and regulatory mandates are more "reasonable."

Further contrasting the electronics industry, other key integrating characteristics have not developed:

- The electrical/electronics industry uses the **exchange and sharing of product data in standard data formats to integrate design** at many critical phases of product life cycle. Conversely, the process plant industry continues to rely on paper as the data of record.
- Also, in the electrical/electronics industry, a **symbiotic growth of computer-aided software tools** based on standardized data formats and content has emerged. In the process plant industry, software continues to emphasize paper documents, not long-life data, as the end product. The growing number of independent software applications used for plant design, construction, and operation are not well integrated.

- In the electrical/electronics industry, the high integration of data representations and software tools is **enabling new types of work practices**, feasible only in such highly automated environments. In the process plant industry, paper-based processes continue to dominate most projects and job elimination seems to be the one goal of corporate downsizing. The process plant industry uses little re-engineering of existing work practices using more efficient design tools.
- In the electrical/electronics industry, noted for short product life cycles, the highly integrated work processes and products make them **more responsive to new and changing customer requirements and other constraints**. Contracting practices based on paper-based project phases, currently used by many E&C firms and plant operators, do not properly incorporate the rapid changes in market needs, regulatory, and professional constraints.

In many of the new business processes realized in the electronics industry, such as on-board diagnostics replacing technician-based diagnostics, behavior models translated for software development, and other innovations benefit from data produced early in the design and production process.

Plant owners and operators now realize that new market realities and regulatory imperatives require radical changes to the classical operational methods inside domestic plants and will soon be duplicated worldwide. Process plants must be designed to produce a broader range of products such as feedstocks, while minimizing invested capital, waste products, and operational costs. The 1989 Phillips 66 explosion in Pasadena, Texas, which killed 23, injured 130 and did $750 million in damage, spelled the effective end to using less expensive and educated contract workers as substitutes for better trained and informed workers. New regulations from OSHA, The Environmental Protection Agency (**EPA**), The Department of Transportation (**DoT**), and many other regulatory and professional authorities require that workers and surrounding communities be informed about and protected from plant hazards and catastrophic equipment failures. While other extremely competitive and highly regulated industries have prospered by improving customer responsiveness, operator protection and downstream work processes, plant designers and operators talk of fleeing to less regulated countries, albeit far from their U.S. markets.

Current efforts to automate certain work processes within the E&C and operations stages of plant life cycle have met with mixed results. E&C firms show that they can change their (project) phase's work data products and practices for the better, but have difficulty in efficiently supporting other work practices with the same data. For example, the paper-based P&IDs drafted during design and provided adequate support for engineering design tasks were not easily updated for several tasks needed to meet certain regulatory requirements. Without a clear strategy for integrating design data products and business processes using **CAX** (Computer-Aided Design, Drafting, Engineering) technologies, and with a business case supporting the plan, industry can not or will not invest for long-term gains in design and operational tools. Instead, money will flow instead to plant production and other improvements. For example, Electronic Data Interchange (**EDI**) remains a strong area of active implementation in process plants because of its obvious return. However, design data delivery among engineers, constructors, and owner/operators is less vigorous and with documents or files of very little asset value, because its downstream returns are less obvious. Still, future regulatory demands and the growing complexity of standards governing plant work practices will make such E&C deliveries imperative!

The symbiotic growth of new business practices in plant operations and diligent maintenance of digital data assets cannot occur until such assets are readily available and usable. Standard formats and contents of engineering information are needed to enable software developers to reuse them. Since those assets are created during design and construction, they need to anticipate the needs of operations and maintenance. The current contractual SOW is too task- and phase-oriented to adequately reflect the needs of downstream users. There is not yet a consistent framework of organizing all life-cycle requirements (constraints) so they are visible to engineering and design.

This study addresses certain specific problems that prevent the process plant and related industries from achieving efficiencies close to the electronics industry. These problems are:

- Failure to consider the life-cycle plant constraints during engineering and construction where most plant data is created. As a result, some data has not been verified against operational, maintenance, regulatory, training, and other requirements.
- Failure of existing E&C plant data deliverables to support downstream tasks. As a result, some data is delivered in formats which are inappropriate for further use, or in formats where critical data elements and relationships are missing or unsupported.
- Failure to adopt new business practices which create appropriate life-cycle data and other new practices that benefit from this new data. As a result, new levels of work process efficiency are never realized.
- Failure of existing systems and procedures to maintain integrity of existing data. As a result of this, numerous additional manual tasks are required to revalidate various data elements (i.e.: P&ID's, plans, and instrument loops). Such corrective work adds no value to well-maintained product data and should be eliminated.

These problems are explained in Section 2 (Sources of Design, Construction, and Operation Constraints) in terms of a broad framework of life-cycle constraints governing plant engineering design and operational processes. Using such a framework, we demonstrate how high, value-added design, operation, and maintenance work processes (tasks) can be selected with identification of data that can be delivered, held for access, or even shared.

The approach makes clear the kinds of new integrity constraints faced by E&C firms acting as agents on behalf of their owner/operator clients. Although work is delegated through a contract SOW or other vehicle, E&C work is driven by the same commercial, regulatory, or technological constraints as their clients. The perspective runs counter to the prevailing view that work is packaged into "phases" and responsibilities do not extend beyond the explicit SOW. The new framework enables improved functional models of design, which are currently based on such "phases."

In **Section 3**, we show how E&C constraints are determined from Root Constraints requirements. Root Constraints can originate in the enterprise's business case for the plant design or modification, in preferences by the agents who realize the plant, or from external sources, including regulations, physical and judicial laws. We analyze how a typical external constraint from OSHA for mechanical integrity impacts the work practices and products of design and construction, even though the regulation is imposed directly on the owner/operator (in his role as the employer). This regulation calls for data elements and relationships to be present in the operational plant and its workers trained for certain work processes. The potential for E&C support of these downstream processes is enormous.

In **Section 4**, we present a typical business case for electronic capture of plant data, specifically P&IDs. It is estimated that if updates are made to single-source P&IDs (i.e., a common database) and quickly re-issued, an estimated $900 in non-value-added work (e.g., rechecking suspect data and reconciling multiple authoritative source documents) is eliminated. This estimate neglects beneficial support of other concurrent and downstream processes, including materials acquisition and process hazards analysis.

In **Section 5**, we conclude that application of the framework to E&C work will greatly improve the integration of data products and processes in process plant design. The framework we present applies not only to green field construction but also to the modification of existing plants driven by business considerations, external factors and other changes in applicable constraints.

A research agenda is recommended to support the transition to this more efficient work environment. Research is proposed to develop:

- New business practices needed to support life-cycle work.
- New formats, application protocols, or other interfaces requiring high discipline validation and consensus.
- New workflow and other data protection controls necessary to enforce data integrity.

2. Sources of Design, Construction, and Operation Constraints

This study presents a general framework for considering comprehensive sources of design constraint in petrochemical process plants and the character of Information Technology (**IT**) that must support them. The study is based on a general theory of rational design (Beazley, 1994) developed by the Information Integration for Concurrent Engineering (**IICE**) program, to capture design rationale (**IDEF6**). This general theory leads to a plant design specific framework, clearly showing the impact of several categories of root constraint on baseline constraint and functional processes seen at various stages of plant design. By considering these root constraints in selecting work processes (tasks) and products (physical products and their associated data), higher valued added work is performed and more life-cycle needs are supported.

The common practice of relying on project phases to suggest functional processes is challenged as leading to engineering- and construction-specific baseline constraints. Just as the engineering process creates product data intended to support construction processes (mostly occurring in the immediately following phase), the engineering process should and could easily create data for training, operational, maintenance, and regulatory compliance functions. The engineering process clearly demonstrates the need to consider and maintain the rationale created at design and construction stages for use in compliance audits throughout the life cycle of the plant.

The IICE theory of rational design underlying the framework is derived from the axiom that a **design or enterprise** is composed of a business case (stating its expected benefits from new or changed design or enterprise processes), the agents selected to realize them, and resources. A resource owner or holder "approves" the business case by allotting the resources (in most firms, capital) to realize the processes proposed by the business case. The enterprise is composed of systems of designs believed to realize the enterprise's business case, and resources come from the "owners." Because scale is the only difference, we will often use "the design" and "the enterprise" interchangeably unless confusion might result.

The root sources of rationale for realizing the processes of the enterprise are: **external** (to the enterprise and its agents), the **business case** (of the enterprise), and **agent-specific**. The business case initiates the design (when resources are allocated) and serves as the resource owner's view of the continuing work to realize and benefit from new or changed enterprise processes throughout the life cycle. **External constraints** are not controlled by the enterprise or its agents. **Agent specific constraints** are not traceable either to external constraints or the enterprise business case; Therefore they must be traceable to an agent of the enterprise. Root constraints are rarely viewed in their entirety by an individual design agent, but they are represented by a current working view or (delegated) **baseline** constraint.

This view of design allows us to characterize process plant design in terms of a framework derived from its root constraints, rather than project phases or other preferred sequences and/or groupings of functional processes. The framework is independent of time and focuses on **delegation of constraints to agents** (to be realized) rather than the less articulate, subcontracting practices seen today. For example, in subcontracting, participants need to look beyond the specific terms of the contract. Agency implies providing the subcontractor with full access to, visibility of, and responsibility for the root constraints and the rationale tying them to a delegated local baseline constraint.

2.1 Root and Baseline Constraints

Design rationale is a system of arguments based in a context, defined as the baseline constraints. Decisions already made and "approved" (baseline artifact configuration) are facts. Baseline rationales are "approved arguments" that relate the baseline artifact configuration to the highest level design descriptive and prescriptive constraints. Generally, baseline rationale arguments are always assumed to be true if the baseline constraint is obeyed. Baseline constraint must be maintained since they themselves are "approved" assertions about "approved" facts (baseline artifact configuration and other baseline data). We will refer to baseline rationales as though they always include any baseline data unless it causes confusion.

The theory of design proposed in the IICE IDEF6 study shows that agents:

- consider the current baseline constraint,
- propose a new baseline constraint with arguments (rationale) that asserts that the new baseline constraint satisfies the old.
- If the baseline and arguments are approved, the proposed baseline becomes the new baseline. The proposed rationale joins the existing baseline rationale to become the new baseline rationale.

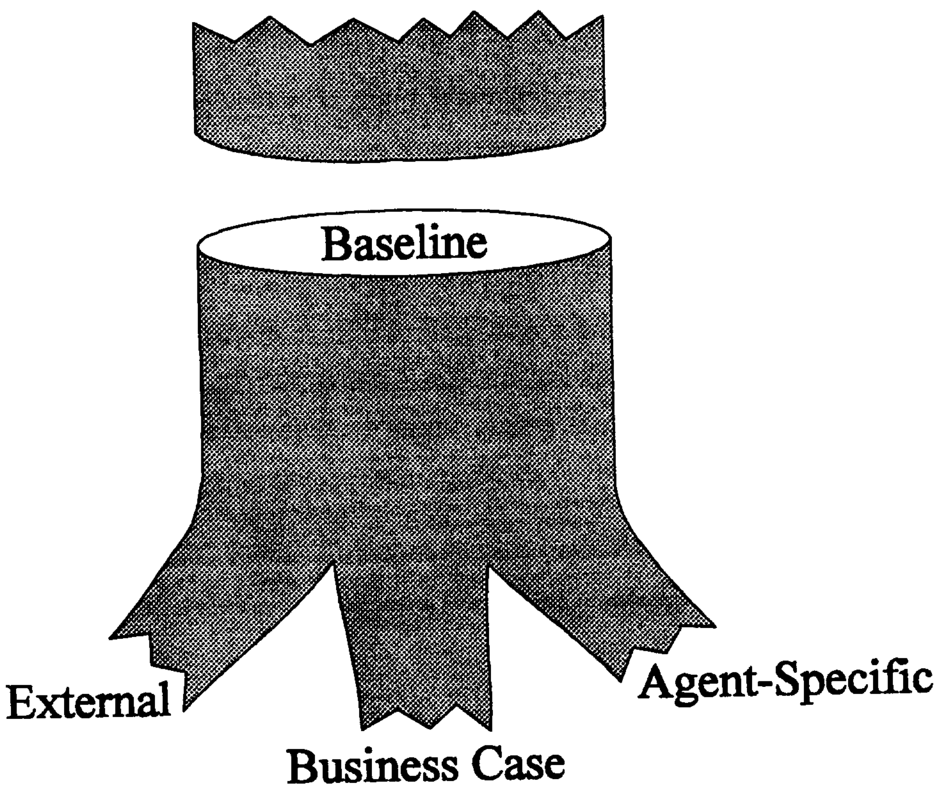

Figure 2.1.1 - Root and Baseline Constraints

It is reasonable to ask that if all rationale is based in other constraints, what lies at the root of these argument systems? For an enterprise of a business case and the agents that realize it, we divide root constraint into three mutually exclusive, collectively exhaustive sets of arguments (See Figure 2.1.1):

- **Business Case Constraints** are the original resource holder's approved rationale that initiates and sustains a process or process change in approved ways. The target process usually implies the functionality of certain artifacts (tools, procedures, and skills) and presents the highest level (business case) configuration. The rationale argues that the changes yield certain benefits and can be implemented using certain resources.

- **External Constraints** point to physical laws, civil laws, professional codes, and standards, and other nonnegotiable and nonchangeable (from the point of view of the resource holder and agents) requirements on the design artifacts and their realization.
- **Agent-Specific Constraints** support beliefs or policies originating within those carrying out the design.

All well-constructed design rationale is traceable to these root rationale and is developed at each incremental refinement to maintain the baseline constraints. The result represents a system of arguments traceable to one of these three sources.

In Petrochemical Plant Design, root sources are very complex (see Figure 2.1.2):

- **External Constraints** are a vast array of environmental, safety, and other government regulations, multiple industry standards, and recommended practices set by professional engineering organizations, and new technologies.
- **Business Cases** now are forced to include costs over the entire plant life cycle including land remediation and restoration, various contingent liabilities from spills and releases, increasingly restrictive operational limits and conditions, as well as unsympathetic market forces.
- **Agent Specific Constraints** include various E&C corporate strategies, and maintenance contractor preferences.

Most design rationale quickly develop from these three roots into complex interdependent arguments. Root constraints are transformed into current working views (baseline constraint) through refinement, delegation, and revision as discussed. Refinement adds detail to the baseline constraint (baseline products and processes) and baseline rationale (traceable to the root constraints). Delegation assigns responsibility for parts of the constraint to agents. Revision is required if the constraint is violated.

External

- Occupational Safety & Health Administration (OSHA) - Safety (Inside Facility Fence)
- Environmental Protection Administration (EPA) - Safety (Outside Facility Fence)
- Securities Exchange Commission (SEC) - Investor Access to Information
- Federal Energy Regulatory Commission (FERC) - Public Energy Policy
- American Society of Mechanical Engineers (ASME) - Mechanical Engineering Integrity
- American Petroleum Institute (API) - Procedures and Practices
- Chemical Manufacturers Association (CMA) - Procedures and Practices
- State and Local Laws - Public Safety
- Physical Laws

Business Case

- Market Forces
- Enabling Technology
- Money
- Skills
- ROI Targets
- Legacies
- Cost of Remediation and Restoration
- Operating Costs

Agent-Specific

- Owner preferences
- E&C Preferences
- Subcontractor Preferences
- Employee Preferences
- Proprietary Technology

Figure 2.1.2 - Selected Sources of Plant Design Root Constraints

Elements of the preceding lists (Figure 2.1.2) do not have an equal impact or duration on the baseline artifact configuration. The OSHA rule for Process Safety Management rule (focused on safety inside the plant's fence line) and EPA's rule for Risk Management Plans (focused on safety outside the plant's fence line) were promulgated in 1992-3 time frame (although they have been discussed for years). Security and Exchange Commission (SEC) rules regarding recognition of remediation and reclamation costs in the balance sheet are also relatively new and impact the market value of the company. From most viewpoints, external constraints from the laws of physics are timeless.

It is important to note that the inequity of these root constraints is not static. What has an overpowering impact at one time can have minimal impact later. For example, in the early 1980's when the market price of oil was above $30 a barrel and rising, few if any other root constraints had the effect of market price. One segment of industry will often respond differently to the root constraints than another. Since the depressed price of natural gas has reduced new construction in the gas processing business, the chemical industry has grown.

Delegation and E&C Firms

Process plant owner/operators to customarily employ Engineering and Construction (E&C) firms to design and build the plant, and the proposed constraint framework must support this important division of work. During the design and construction phases of petrochemical plant life cycle, the need for specific data sets, work processes, and integrity relationships has never been greater. These additional constraints have been placed upon plant operators and, either explicitly or implicitly, the E&C firms that design and construct plants. This is true for green field facilities, as well as for modifications to existing plants. All these additional design constraints must pass down from the owner/operator to the E&C firm.

E&C firms are accustomed to working to a company specified SOW in contract documents. Many of the specifications found in those SOWs lack a rationale clearly traceable to root constraints. This practice fails to represent to the E&C agent true responsibilities and liabilities in the plant they are designing. In addition, many plant owner/operators are unable to completely express, through the contract specification mechanism, the data sets, work processes, and integrity constraints requiring documentation in the plant.

The problems in E&C contracting appear in other owner/operator business relationships. The practice of "outsourcing" tasks to subcontractors, formerly restricted to mainly E&C tasks, has been extended to operations, maintenance, training, and other tasks. Hiring contractors had important salary and pension cost benefits and shielded the owner/operator from other liabilities arising from direct employment. Some types of root constraints have highlighted the inadequacy of the "arms-length, owner/contractor" relationship, particularly where it purports to shield the owner from liability for contractor actions. For example, the recently promulgated OSHA and EPA safety rules for process plants (external root constraints) make owner/operators responsible for certain actions by other agents, such as employees, contractors, and subcontractors. The actual extent of the expanded liability is still being argued, but few maintain that an owner/operators are immune from the negative actions of their agents. Plant safety and operational information must be made available to all persons, including subcontractors, working in areas classified as exceeding threshold quantities of hazardous chemicals. This is particularly upsetting to the owner/operators, who regard their processes as proprietary. Owner/operators must also verify the skills of all employees, including subcontract employees, as adequate to the tasks assigned. This responsibility now essentially flows to the contractors, whose training, testing and other skill certification must be reported back to the owner/operator. Regulatory trends clearly lump contractors, and employees together as agents of the enterprise for plant safety and other purposes.

Similarly, E&C firms are not and should not act and think as hired temporaries but as agents of the owner/operator. As such, the E&C agents must look beyond SOW contract wording to the owner/operator's life-cycle requirements. Much of the training, operations, maintenance data, and work processes involved in meeting the requirements is largely created or determined at design time. If these downstream needs were anticipated, costs could be greatly reduced.

Delegation of constraint within this framework is shown in Figure 2.1.2. The most important delegation in the Process Plant industry is to the E&C type of firms (see Figure 2.1.3). E&C firms are classically delegated the realization of the physical plant, and have optimized their processes around this goal. The framework presented here clearly shows that today their proper role is the realization of an operational systems of products and processes, ultimately compliant with applicable root constraints. E&C firms, however, represent mainly "transitional" processes, i.e., those realize the "TO-BE" products and processes from the "AS-IS" state. The contracting and business processes used in delegating transitional responsibilities to E&C firms must recognize that their work must comply with the business purpose(s), other agent preferences, and external constraints on the operational plant. This has not occurred in the past because of various difficulties caused by the delegation (contracting) process (see IDEF6; Beazley, 1994).

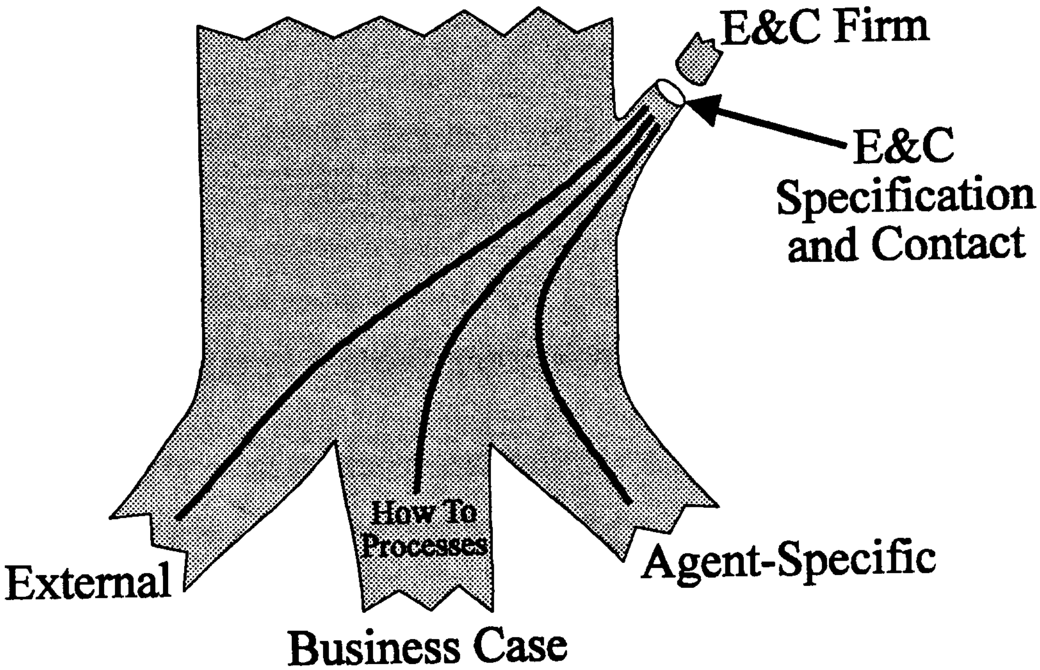

Figure 2.1.3 - Delegation of E&C Responsibility

2.2 Limitations of Prior Functional Process Models

Functional Process Models for process plant design show which work processes and products are associated with this work. In this section, we will compare functional process models derived from the proposed constraint framework to others.

Our understanding of plant design processes and products is essentially different versions our reference identified as the **Phased Design Model**. The phased design model is based on the idea that process plant design occurs in defined phases. Each phase begins with information furnished to the agent, and ends with deliverables to the client. Each phase is controlled by a SOW and external constraints applicable (mainly) to the SOW processes drawn from generally accepted practices known to the agent.

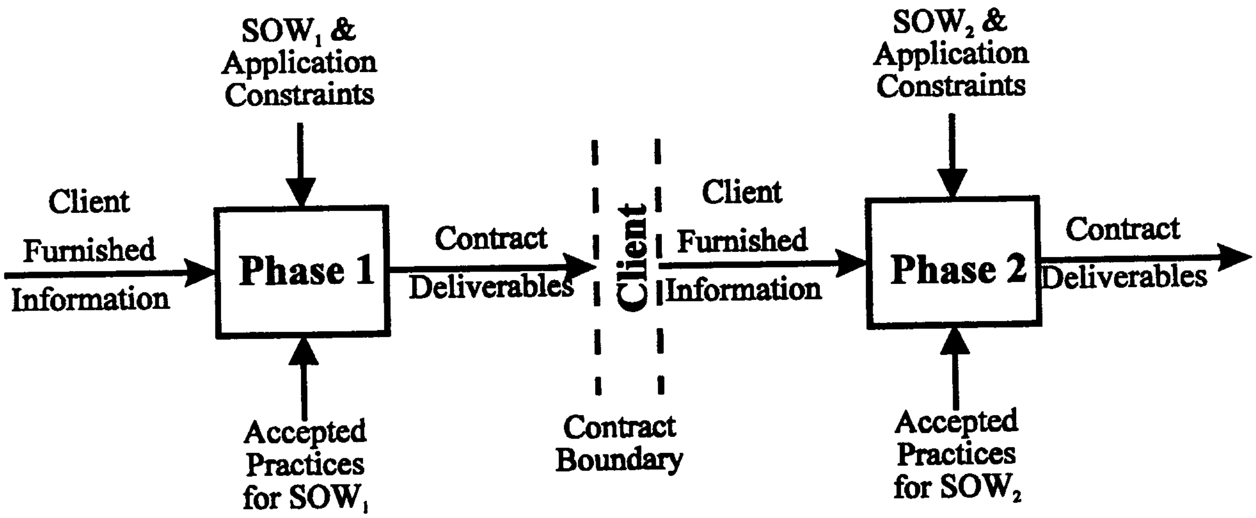

Figure 2.2.1 - Phased Design Model

Figure 2.2.1. illustrates the general situation. Client Furnished Information (CFI) is processed in accordance with the SOW and applicable constraints, using the accepted engineering practices for tasks specified. The result is a deliverable to the client which, after some internal revision, becomes the CFI for the next phase. In most diagrams showing functional processes and products as a phased design model, the hand off to the client is not explicitly diagrammed. This is the case when design phases are presumed to be high-level abstract **design functions**. For example, see the **Process Plant Information Flows Model** (based on the PISTEP Process Plant Engineering Activity Model) in **Figure 2.2.2.** Although clearly functional in intent, it presumes that project phases are abstractions of design functions.

Although extensively used and widely accepted, a phased model of process plant design functions and data delivery overlooks some serious problems. A phased design model does not accurately depict upstream (during an earlier phase) design processes controlled by other concurrent or downstream constraints and controls. This directly results in contractual boundaries imposed between phases, leading to a tendency to look only within the contract for constraints on deliverables. It is arguable that this tendency in contracts is a legacy of outdated practices originally relying on a paper-based data delivery media.

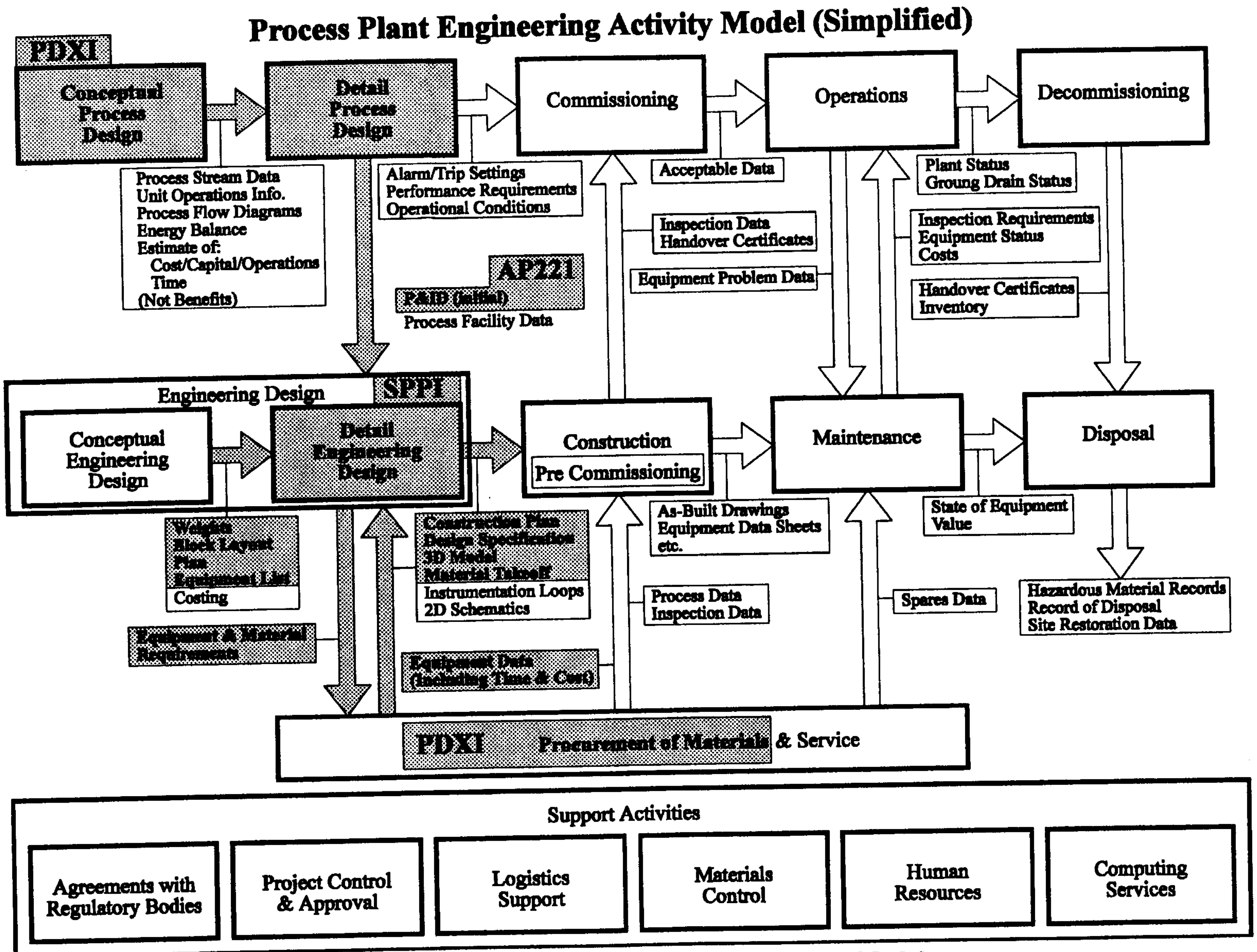

Figure 2.2.2 - Process Plant Information Flows Model
(based on the PISTEP Process Plant Engineering Activity Model from ISO (1994))

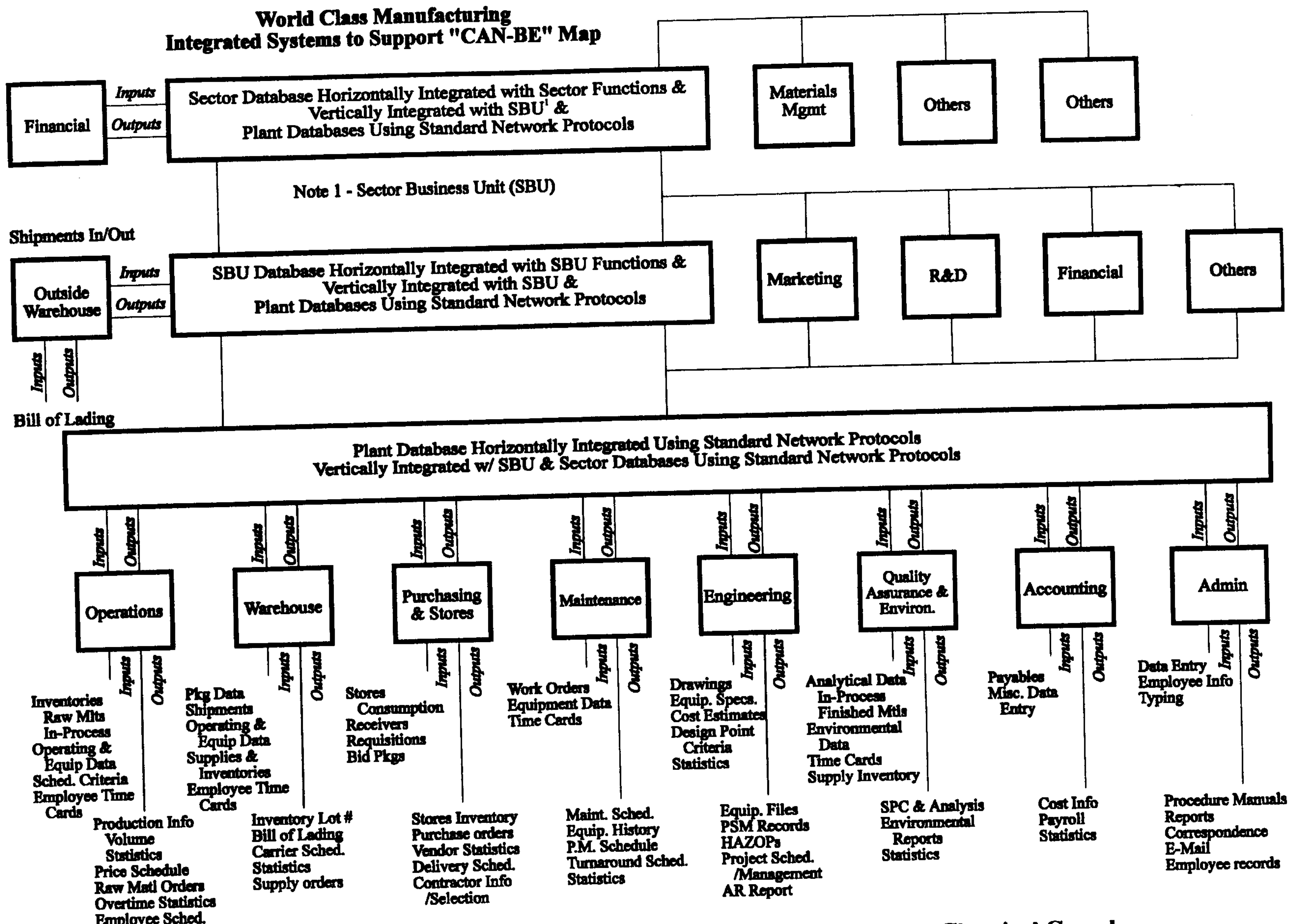

Figure 2.2.3 - Typical Information Plan (CAB-BE Diagram) for a Large Chemical Complex.

In any event, the phased model has led to data products which have little support for other concurrent or downstream processes and products. For example, a piping layout drawings for construction might exclude data and details critical for process hazards analyses, maintenance planning, to an emergency response, or site remediation. Another example is when naming conventions based on plant location or process stream become confusing when equipment is moved around the plant during operations, maintenance, and modifications.

The problem is not limited to the mere absence of needed data elements (pieces of data). The work in Section 3 (Determining E&C Constraints from Root Constraints) shows that data relationships and processes that create and maintain them are also prescribed. For example, process limits imposed by equipment must be aligned with limits used in analyzing hazards or in training, and a process to keep them aligned must be implemented and documented during all stages of design. The pedigree (history) of important stationary equipment must be documented and support recalculations based on inspection results.

In addition, the owner/operator's view of the plant centers on financial and management issues from the beginning of design to the disposal of the decommissioned property. **Figure 2.2.3.** shows a typical information plan for a large chemical complex. All plant activities report to and are subordinate to financial and management issues at higher levels of the plant. This subordination is unclear in phased delivery models, which concentrate on delivery between aggregated work processes.

The bottom-up approach to process plant modeling, exemplified by phased delivery models or even functional activity models based on them, carries with them two problems:

1. The tendency to overlook other concurrent and downstream constraints, leading to poor support for downstream work processes and,
2. The difficulty in showing the higher level of abstraction used by the owner/operator, namely, the financial/management view usually referred to as the business case.

Recursive Design

Design functions are more accurately represented by a recursive model rather than a phased one. Each new version of the plant replaces or enhances the last. In the E&C phases of design, successive versions are mainly **refinements** to enable the plant to be realized. After operations begin, successive versions are mainly **revisions** to the last, i.e., enhancements, debottlenecking, decommissioning, and remediation.

Table 2.2.1 shows the versions of a typical process plant and the kinds of analyses which govern their transition. The framework established in this current work supports recursive design. A recursive design model should be consistent with the constraint framework presented here. Obviously, the successive baseline constraint and linking rationale is consistent with refinements and revisions of functional design processes.

Typical Depth and/or Type of Analysis	Old Version	New Version
Market OK	Green field	Conceptual Process Design
Simulation OK	Conceptual Process Design	Detailed Process Design
Preliminary Cost/Benefit Estimates OK	Detailed Process Design	Engineering Design
Final Cost/Benefit Estimates OK	Engineering Design	Procurement
Delivered Cost & Schedules OK	Procurement	Construction
Pre-start-up Reviews OK	Construction	Commissioning
Acceptable Performance	Commissioning	Operations/Maintenance
Capital Request OK	Operations/Maintenance	Modification 1
Capital Request OK	Modification 1	Modification 2
Capital Request OK	Modification 2	Modification 3
Capital Request OK	Modification 3	Modification 4
• • •	• • •	• • •
Capital Request OK	Modification n-1	Modification n
Mothball Request OK	Modification n	Decommissioning
Liquidation Request OK	Decommissioning	Facility Disposal & Remediation

TABLE 2.2.1
Versions of a Typical Process Plant and the Kinds of Analyses Which Govern Transition

Furthermore, process plant data should be defined to meet other concurrent and downstream constraints and be capable of supporting other concurrent and downstream processes. The baseline constraint and rationale concepts used in the framework of this paper can be used to identify all constraints know to exist at any stage of design. The baseline constraint captures, through the business case abstraction, all processes and artifacts of the design and its realization. A simplified functional model of a recursive design is shown in Figure 2.2.4. A more complete functional model of process plant design consistent with the framework of this paper is presented in **Appendix D**.

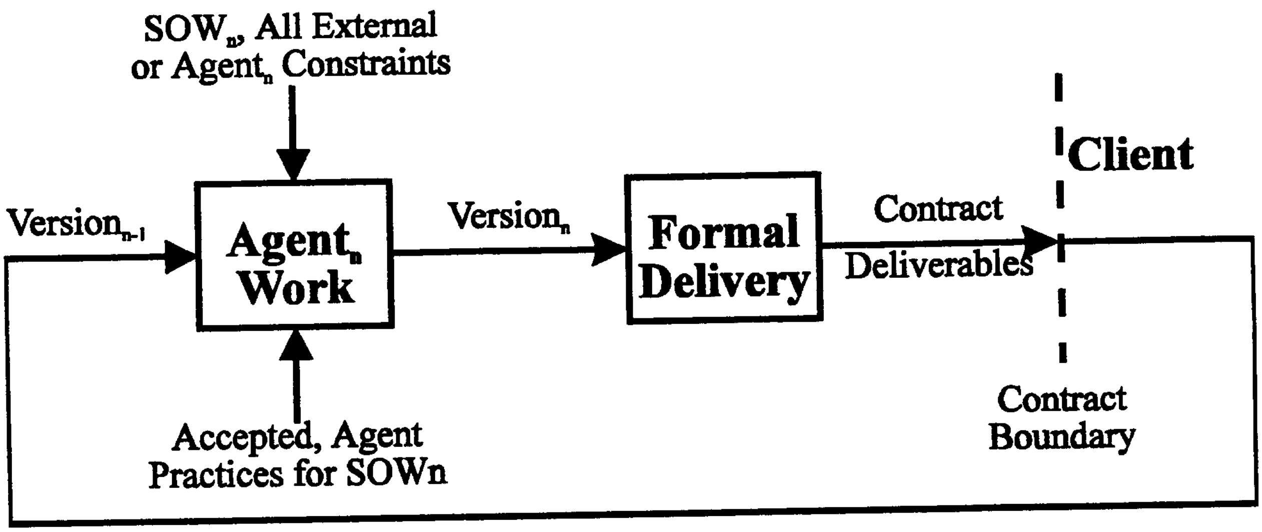

Figure 2.2.4 - Recursive Design Model

2.3 Process Plant Business Case Issues

The ever changing root constraints governing process plant design and life-cycle operation have been reflected in changes in plant (design work) products and processes. As one of the biggest cost factors in both realizing and operating a process plant, increases in labor costs are affect the way plants are designed, constructed, and operated. Organizations are doing quite well re-engineering work practices so that less staff does more. This section discusses certain issues in deciding if such reductions are good business decisions.

Business cases are holistic documents which address the transition from old and new business practices involving a broad spectrum of design artifacts, explicitly and implicitly. A business case for process initiation or change must define:

- What processes are to be realized (TO-BE Processes).

- How to realize them from the existing processes (AS-IS, HOW-TO Processes).
- What is needed to realize them (HOW-TO Process Resource Consumption)
- What is the expected result.
- Why the expected result is desirable to the holder of the required resources.

It is not merely design artifacts (TO-BE processes and the products they use) which are refined by design work processes, but the total business case, as a system of facts and arguments. Although design artifacts and associated technical rationale are part of this system, they play a major part. All refinements to the business case are valid if a rationale proves them so.

Synergistically, the computer-aided work process improvements today are supported by computer technology. The difficulty arises in that of the many improvements possible, not every one contributes beneficially to the support of downstream plant life-cycle processes. Some improvements later found to be limiting are:

- Computer applications that rely on nonstandard or proprietary data formats that cannot be converted to formats needed by downstream processes.
- Improvement of individual tasks without regard to integration within and across organizational boundaries.

As a result, some E&C firms and plant operators realize an immediate and measurable benefit. Later they find that, as these applications proliferate, the improved work processes and products are incompatible with others required during the plant life cycle.

As a result, various specific tasks are being hurried while little re-engineering of processes occurs. Additionally, locally maintained databases incur combination and reconciliation process costs to maintain integrity of redundant data and inter-database relationships. In other words, the negative of this change is that the business case developed for point applications lacks the efficiencies of proper integration and thus does not anticipate all contingent costs.

The data products exchanged between these "islands of automation" are usually designed to emulate or even retain the legacy paper link between them. A report, diagram, or engineering drawing is printed out only to be re-entered, often manually, into one or more downstream process applications. In other situations, data is exported from one computer system into an ASCII text file or a proprietary data format only to be translated for importation into another system. The content of these data transfers should be designed to support downstream processes and should be exchanged using protocols and formats capable of encoding sufficient data elements and relationships.

Concisely, the proposed, constraint framework calls for business cases that derive from the owner/operators rather than from local E&C considerations alone. If this were the case, then extra work incurred at design and construction time could be justified and life-cycle limitations could be identified.

2.4 External Constraints in Process Plants

External constraints are laws and codes imposed on the design forces outside of the control of the resource owner or design agent. These include physics, governmental laws, regulation, and professional codes and standards (as representations of "normally accepted practice"). Although this category is broad, the treatment of such constraint is remarkably consistent. Other workers have shown that the expression of such external constraints leads to argument systems identical to those found in most Requirements Management Systems (RMS).

The encoding of engineering standards was studied in great detail in the design of SASE (Standards Analysis, Synthesis, and Expression), a system for encoding and maintaining engineering standards (see Fenves, et al., 1987). A standard is a set of rules that must be evaluated to determine compliance with the purpose of the standard. The evaluation of a rule may depend upon other rules in a recursive fashion. The overall organization of the standard can be completely described in terms of the organization of those rules that are requirements.

Finally, in the following Section, we will demonstrate how selected external constraints have a direct, traceable impact on E&C products and processes.

3. Determining E&C Constraints from Root Constraints

As established in Section 2, there are three root sources of design constraints. Table 3.1 summarizes some of the key characteristics of each type of constraint. A key criticism of prior functional process models was its derivation from design phasing considerations. There is little experience, however, in using the constraint framework to determine the character of front-end processes and products. In this section, we demonstrate, using real regulatory language, how external root constraints aimed at plant operations can be partially supported by E&C design products and processes. Of importance, we show that at least part of the content of design data is not defined by the needs of local phase tasks, but by longer-term life-cycle tasks.

Root Sources of Design Constraint	Owner/Approver	Argument Qualification, if traced to ...	Content/Role
Business Case	Resource Owner	Defensible	Justify Process Initiation or Change
External	External Powers	Defensible	Regulation/Physical Laws
Agent-Specific	Agent	Defensible	Agent Preferences/Beliefs

Table 3.1 - Key Characteristics of Root Constraint

External constraints were chosen for this demonstration because business case and agent-specific constraints have been developed in a separate study. It is generally acknowledged that external constraints have the greatest impact on process plant operations but their impact on E&C products and processes is less well understood. The IDEF6 report demonstrated that business case constraints control the features of design artifacts which are important to the enterprise. The SASE work of Fenves, et al. demonstrated the capture of engineering standards for automatic use during design. To expand external constraint analysis further, we now discuss the analysis of regulations and citation language for design and construction impact.

3.1 External Root Constraint Example

A specific root or descendant constraint impacts E&C work products and processes in at least two ways. First, it directly determines the nature of E&C products and processes. Second, it directly determines the nature of parallel or downstream products and processes; the E&C products and processes are adjusted to better support them.

For example, the OSHA 1910.119 PSM rule dictates that there will be a pre-start-up safety review (an E&C process requirement). It also requires that process safety information (**PSI**) be made available to plant operators, including process hazards information (an operational process requirement). However, for new or modified plants, E&C agents are, probably, the best choice to create PHAs which develop hazards information from studying P&IDs and other plant product data. The external constraint on operations has led to a constraint on E&C products and processes.

In work already published (Chapman, 1993), Chapman and Beazley have demonstrated that portions of the OSHA 1910.119 (PSM) clauses can constrain either scope of applicability, data sets required, work processes, or integrity relationships. Portions of that work are now repeated here for application to engineering and constructions phases.

Performance based rules, like the OSHA PSM, can be divided into four types of sections. Some segments are prescriptive and other segments that identify a relationship that must be maintained. Rule segments identify either a:

1. Scope Definition
2. Process To Be Performed,
3. Product To Be Created and Maintained, or a
4. Relationship To Be Maintained

Since the items are closely and, often inseparable tied together, great care must be taken to document that each type is satisfied. Each rule type is satisfied in a different manner:

Examples of **scope definitions** are:

- "A covered process is ...."
- "...used for fuel are specifically excluded"

Examples of required **products** are:

- "written procedures",
- "documentation"

Examples of required **processes** are:

- "employer shall train...",
- "inspections and test shall be performed...",
- "employer shall document...",
- "employer shall correct deficiencies...",
- "checks and inspections shall be performed...", and
- "employer shall assure..."

Finally, examples of required **relationships** are:

- "shall follow...",
- "shall be consistent with...",
- "defined by...", and
- "is suitable for..."

Since each rule type is satisfied differently, the documentation needed to show satisfaction is also different. In practical terms, scope definition is part of any of the remaining three.

Appendix B shows the analysis of OSHA 29 CFR 1910.119 (Process Safety Management) part j, which controls the mechanical integrity of operating plants. Despite the operational performance implied by the PSM rule, **Appendix A** clearly shows the applicability of certain constraints to E&C products and processes.

To further illustrate the point , **Appendix C** shows the analysis of actual citation language issued to offending process plants during the Petrochemical Special Emphasis Program (**PetroSEP**) used by OSHA to develop the PSM rule. Note that a large fraction of citations refer to data, work or integrity relationships first established during design and/or construction.

E&C work, which ignores these types of constraints, would be clearly inadequate for owner/operator use; however, this is often the case. Even in well engineered and documented projects, the plant data is delivered to the owner/operator in formats (paper) requiring manual or manual-like (e.g., computer-aided drafting) processes to be maintained. Clearly, this cannot continue.

3.2 Data Types and Supporting Tools

Table 3.2 compares the type of requirement to the methods used to confirm compliance (process) and the type of information that documents compliance (product) and the software tools available to support them. For example, relationship constraints are often applied by the OSHA PSM rule to assure that certified procedures have been used in operations and maintenance. One method of checking if these relationships are maintained is the integrity check performed in database management systems. Another check is the management of change review where a change to products and/or processes in one area is reviewed by other areas for their effects. The dependencies themselves are documented in data mapping and or document dependency diagrams and successful preservation of integrity would be shown in an integrity report. Support for these integrity products and processes are found in generalized Engineering Data Management Systems (**EDMS**)and in translators or reflavorers.

By reviewing some of the types of items required in Table 3.2, one can see that these data systems (whether paper or electronic) must be in place during construction, not just when the plant is in operation. Some data is required early in the construction phase (i.e., inspection reports or certifications), and other data is required during plant start up (i.e., standard operating procedures (SOPs), Material Safety Data Sheets (MSDS). It is too late to wait until the plant life cycle is operational to have this data in place.

	Scope	Process	Product	Relationship
Typical PSM Application	Covered Processes	Work Practices	Data Sets	Certified Procedures
Method of Compliance Verification	Classification Study	Audit, Step Review	Certification, Inspection, Inventories	Integrity Check, MOC reviews
Typical Documentation	Classification Report, Equipment Survey	Written Procedures, Audit Trail	MSDS, Databases, CAD Drawings	Data Mapping, Dependency Diagram, Integrity Reports
Example Tools	Automated Checklists	Workflow Mgmt, EDMS	Forms, Data Dictionary, CAD Standards	Translators, Re-flavorers, Interfaces, EDMS

Table 3.2 - Rule Applications, Compliance Methods and Type of Documentation

Since the design and construction phases are so tightly linked, one must deduce that these data systems must be planned during the design phase as a regulatory mandate. This, of course, exacerbates the problem of data integration.

4. A Business Case for Electronic Capture of Plant Data

In the last section, the constraint framework proposed in this study was used to identify functional processes needed to refine the design and justify design decisions. Once the required work processes are identified, the cost of those processes can be assessed. If technology were available to improve those processes, the benefits of these improvements can be compared to the old and new process costs. In this section, we demonstrate how such assessments can be used to estimate the return on investment in process improvement, particularly when using certain data exchange or data sharing technologies.

One notable problem in introducing CAX technology into process plant design is that the existing infrastructure is built around its paper-based work practice legacy. This includes the legacy contract language and laws that inhibit change. Although individual business cases can and will target specific AS-IS processes and products for change, the general nature of contracting in the process industry, particularly E&C services, resists the change to highly automated TO-BE processes and products. It is worthwhile taking time to review the context in which such business cases are advanced.

4.1 Impediments to Automation in Process Plant Design

Business cases for data exchange and sharing between work processes in Chemical Process Plant design must address several institutionalized impediments:

- The cultural impediments to digital design data delivery.
- The need to change work processes to maximize benefit from downstream digital work products
- The importance of specifying data formats and application protocols for digital deliverables
- The need to maintain digital data as a long-term asset

The Cultural Impediments to Digital P&ID Delivery

Most owner/operators agree that there is some value in taking delivery of design data in a compatible format with their in-house CAD systems. Why doesn't this happen? Instead, for a variety of reasons, design definition and other product data generally come from the E&C firms and other contractors on paper:

- Often, a licensed professional engineer must sign the drawing or document. This requires paper media. The legal standing of electronic signatures is still relatively new in commerce.
- Undervaluation of design data assets in specific formats excludes them from the contractor selection process and, if part of contract requirements, softens their enforcement during work performance.
- Some owner/operators are not equipped to accept CAD drawings in formats inconsistent with their internal CAD systems, or they lack CAD capabilities.
- Some E&C firms avoid delivering CAD-ready data to owner/operators as a business strategy designed to keep them returning for changes.
- The E&C firms structure CAD data (symbol sets, non graphic properties, layering conventions) in ways that optimize design and construction but are poorly organized for downstream uses.

This leaves a **large initial cost** for an owner/operators to convert P&IDs and other design data to a compatible digital format. When required by some later business process, some owner/operators have little choice but to redraw many of the drawings using in-house (or contract) labor. This occurs if the data has not been updated to reflect changes to the plant. In such cases, the cost of recreating the digital data cuts deeply or eliminates into the value of downstream processes that are enabled. For example, because of the key role P&IDs play in PHA's, many P&ID's are being redrawn as a result of OSHA and EPA rules requiring PHA's, as well as requiring the availability of updated P&ID's to plant personnel.

The Need to Change Work Processes to Benefit from Digital Data

In addition, many owner/operators lack the infrastructure to use digital plant data beyond the maintenance and re-issuance of revised drawings. Owner/operators lack the experience or capital to implement systems and other downstream applications which could benefit from any or all of the several digital representations possible for P&IDs and other digital plant data. For example, selected processes which benefit from the existence of current P&IDs include:

- Digital storage and retrieval of drawings
- Automated document configuration and work flow management
- Print- or fax-on-demand documents for maintenance
- Plant operator access to PSI data, including access via compound documents or hypermedia derived from product data.
- Integration with materials control, including automatic Bill of Materials (**BOM**) and other extracted input data.
- Performance of PHA and other processes required by OSHA, EPA, DoT, and other regulations and by ANSI, ASME, API, CMA, and other professional recommended practices.

We will use the latter process to estimate the quantitative business case for digital delivery of P&IDs.

The Importance of Specifying Application Protocols for Digital Deliverables

The utility of delivered data for any particular purpose is not a foregone conclusion just because it arrives in digital format. For each of the processes listed above, certain formats and encodings are required to insure that value added by the E&C firm is appropriate and delivered for later use by the owner/operator. Extra data elements and relationships, added at the time of creation solely for the owner/operator (i.e., owner/operator task codes), must also survive any encoding in a delivery format. To further complicate the data exchange, situations can occur where another group other than the E&C firm produces the initial P&IDs on a different type of system or data organizational methods used by either the E&C or owner/operator. Added value in one system must be preserved at delivery time for use in the destination system.

For product definition data, such specifications are usually referred to as an Application Protocol (AP). APs contain information models describing the data to be encoded and decoded for delivery and a mapping to an agreed format. Several standard (vendor-independent) APs are being developed for data exchange in national and international standard formats, including two important product definition formats, IGES and STEP. Whether data is delivered or shared, APs protect the content and integrity of the data by limiting access to controlled channels (formats and queries) with an agreed, documented mapping to the data. The added value of using standard, vendor-independent APs is that the data content is common across a wider range of processes that can benefit from electronic access to the data. In other words, the value in any data format is determined by the value and number of processes that can use it, and the value of standard formats is its ability to attract support from more (process) application vendors.

In the process plant design community, the level of awareness and skill in creating and using APs is still quite low. The technical understanding of how to negotiate and document data content and mappings is rare among the engineers in both contractors and owner/operators. This understanding is almost nonexistent and rarely appreciated among the project management who must fund and support its function on the job.

The Process Changes Needed to Maintain and Benefit From Digital Data

McGill and Waltz (1994) said that a recent internal survey of Administrative, Operations, Maintenance, and Engineering personnel by a petrochemical company found that maintenance and engineering employees were the most thorough searchers for engineering data and the most skeptical regarding the accuracy of equipment documents. They frequently searched for data in multiple locations and were not surprised when two or more separate and somewhat different documents were claimed to be the authoritative source version.

When plant data is suspect or its availability unreliable, a vicious cycle occurs. Current processes make retrieving plant data from the drawing vault unreliable. Hence, operations and maintenance personnel keep extra copies of drawings in their work areas. Markups made to local copies resulting from errors and changes are not returned to engineering. Confidence in engineering data erodes. Plant walk throughs and other non-value-added work processes are needed to verify data that is t considered untrustworthy.

Recent rules from OSHA and EPA require that plant operators have access to PSIs to understand the hazards in the plant. This requirement alone implies that the practice of correcting data prior to its use violates both the PSM rule and the RMP rule.

More important than regulatory constraint, however, is that none of the predicted benefits are possible until practices that maintain the integrity of the data are implemented. Current data would eliminate the costly, non-value-added, and possibly illegal practice of verifying the correctness of plant data immediately before use. It seems natural to expect that if these practices benefit existing plants, they would be even more beneficial if data integrity was maintained from the time the plant was constructed throughout the entire life cycle of the plant.

4.2 Qualitative Business Case for 3D Plant Data Models

One particularly difficult area to quantify is the business case for 3D plant data models used during design. For example, before 3D CAD models were available (see Figure 4.2.1), very detailed plans and elevation drawings were required. Many items were identified in all drawings where they appeared. The reason for this need (for redundant data) was that no true link (interface) existed between the plan
and elevations nor any of the downstream data items produced such as isometrics, or BOM. In addition, the highly detailed plans and elevations helped manual checkers who inspected all of the work. A common problem was that the one or more data source was inconsistent with another. Those errors had to be found and corrected (data reconciliation). Data reconciliation

adds no value to the body of design data in terms of refinement; it assures integrity between two data bases where data is related and/or redundant.

Today, 3D CAD users completely eliminate separate plan and elevation drafting processes (see Figure 4.2.2). 3D CAD systems can produce any view of a computer model (single and/or double line plan, elevation, or isometric view), as well as downstream data sets: detailed isometrics, spool drawing, or BOM. Since all abstractions of the data are directly derived from a single source, data inconsistencies are eliminated. The costly and time-consuming process required for checking and correcting inconsistencies has been eliminated because the errors have been eliminated. To truly benefit, an organization must use a 3D CAD systems technology to re-engineer their design processes to generate, rather than redundantly draft derivative documents.

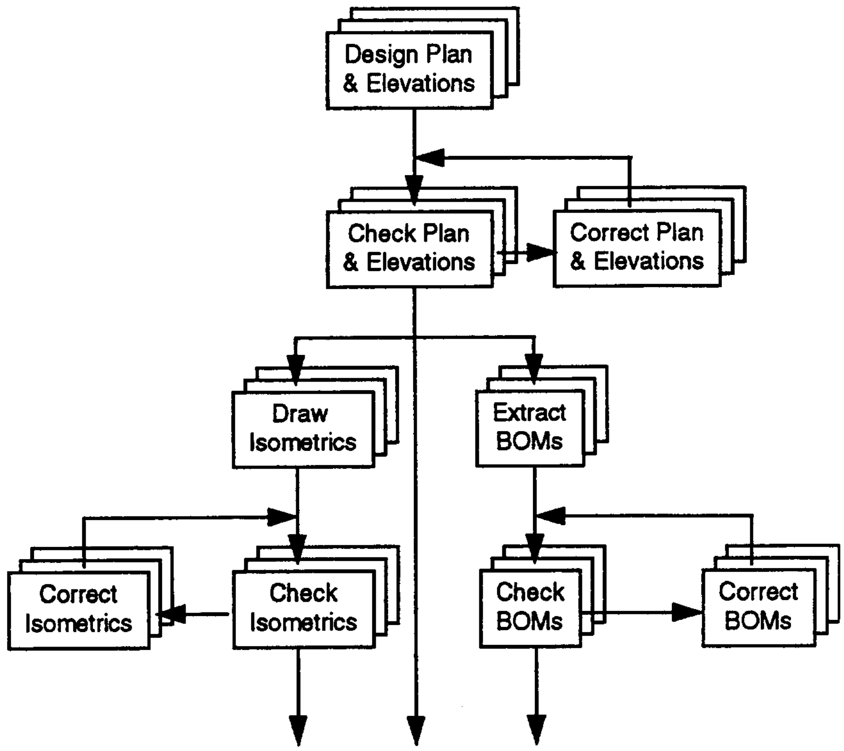

Figure 4.2.1 - 2D Method of Plant Design

As a direct result of this re-engineering, the plan and elevation drawings have a more limited purpose. Their new role of the plan and elevation is mainly limited to overall piping layout check and construction assembly. Checking for such as item clashing, connectability, or material spec compatibility are found more quickly and accurately in computer analysis of the 3D model. Checkers now have the option of reviewing the actual 3D model or the plan and elevation. Iso's, spool drawings and BOM produced from the 3D computer model need very little checking.

The content of the plan and elevation is also changed. Fewer elevation drawings are produced and only major items such as line numbers and major components are tagged, since tagging is used to reconcile components that redundantly appear on more than one drawing.

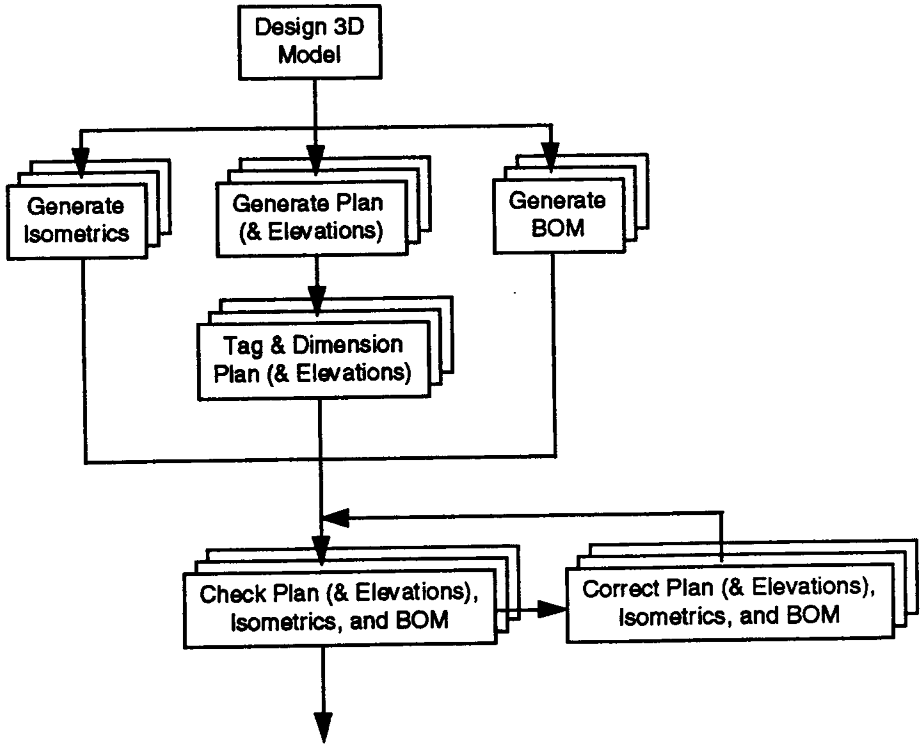

Figure 4.2.2 - 3D Model Method of Plant Design

Other downstream processes that can benefit from the use of 3D plant models include:

- EDI transactions for ordering materials (from BOM)
- NC programs used for pipe handling, bending, end preparation, or welding
- real-time 3D model simulation on high performance graphics workstations for design review, construction sequencing, or training
- identification of inspection points in plant
- disaster scenario modeling (vapor clouds, fire, explosions, or spills) which requires spatial information unavailable in process flow diagrams (PFD's) or P&IS's

Thus, the business case for 3D plant modeling would be summarized as follows:

- AS-IS Processes - highly-detailed plans and elevation drawings are constructed and many long-lead time derivative documents drafted in parallel. Much coordination and reconciliation is required.

- TO-BE Processes - 3D models carry all data formerly annotated on plans and elevations and derivative documents are generated after the model is accepted. Coordination and reconciliation is eliminated and other benefits accrue.
- HOW-TO - Designers are retrained on new CAD software while design practices are re-engineered to eliminate plans and elevations as the data of record documents.
- ROI - Improved quality, cycle time, and reduced errors offset the increased cost and management complexity of 3D design.

Although it is hard to quantify, owner/operators and E&C managers have accepted 3D design based on anecdotal evidence. This limited example of E&C data, primarily benefitted E&C processes. The proposed framework shows that E&C data must support a much broader range of re-engineered processes. The next example will illustrate the benefit of downstream process support.

4.3 Quantitative Business Case for Digital Delivery of Plant P&ID Data

A PHA-Driven Business Case for Digital P&ID Delivery

We can develop a business case for digital P&ID delivery from costs being incurred to update P&IDs for PHA's. We assume that if digital delivery of P&IDs is made in a form that can be easily updated and distributed, e.g. CAD, then the wholesale update verification of a P&ID would be eliminated. Furthermore, it is assumed that the cost of the update to the P&ID during normal maintenance activities and subsequent distribution would not change, i.e., that the updating now being done in parallel to private copy updates would not change if updates were always reported and distributed by a central authority. If this were true, then the non-value-added walk-through verifications would be completely eliminated. Fortunately, because many of these P&IDs are currently being updated and verified, we have some cost data upon which to base this estimate.

A PSM cost/benefit survey by William G. Bridges of JBF Associates, Inc. estimated compliance costs per activity from survey responses. Bridges' activity costs are given in Table 4.1. (Bridges presented his findings at the International Process Safety Management Conference and Workshop, September 22-24, 1993, in San Francisco, California, The survey is scheduled to be published in January, 1994, by AIChE in its publication, Process Safety Progress)

The activities in Table 4.1. must be taken less literally than we prefer. For example, the cost to update a P&ID includes both drafting time and in-plant manual verification. The latter cost is often the greater cost. The fully burdened draftsman cost is about $20-40 per hour, depending on the draftsman's experience. Assuming $30 per hour and taking Bridges' average cost to update a P&ID at $1,800, then the update took sixty hours.

Activity	Average	Std.Dev.
Update each P&ID	$1,800	$1,000
Develop an operating manual and training module (per step)	$800	$700
PHA	$55,000	$65,000
PHA/P&ID (all data)	$4,500	$3,000
PHA/P&ID (continuous)	$2,900	$2,300

Table 4.1 - PSM Activity Cost

Most firms are taking this opportunity to redraft their P&ID's on a CAD system, usually with AutoCAD. A really fast CAD operator, with a menu of symbols already designed, can draft a P&ID from a sketch in 10-25 hours, including checking. This means that CAD drafting can only account for $300-750 of the cost of updating the P&ID. What is the remainder?

The remainder of the cost (approximately half) results from walking through the plant, checking the old P&ID for accuracy. This directly results from failing to maintain the old P&IDs so that their data remained trustworthy.

If, however, the drawings were maintained on CAD and printed on demand or on another efficient distribution scheme, and changes were reliably returned and incorporated in the source CAD data, then these non-value-added costs would be avoided. If we recognize half of the Bridge's update cost as identical to the cost of updating on a continuing basis, then the remaining half, say $900, is the potential savings if the drawings were electronically maintained on a continuing basis. A typical large plant has 200-300 P&IDs defining it. The cost avoided is estimated to be $180,000-$270,000 if P&IDs are digitally delivered and maintained on CAD.

Thus, we can conclude that having P&IDs delivered and maintained in easily revisable, electronic form would save approximately $900 per drawing. Even more could be saved if CAD formats were used which supply data for other work tasks. We also observe that these savings occur because certain non-value-added processes, like manual material takeoffs or mass distribution (replaced by fax-on-demand), were eliminated which require that electronic data be continuously maintained.

This frequent and dedicated effort to update and re-release is the compelling argument in favor of process change to electronic document maintenance. For maintenance, operations and other users to return their marked-up drawings to engineering for revision, they must feel that they can quickly and easily get new copies as needed. For a small plant, it might be possible to provide quick and dependable revisions to critical documents. For moderate plants or larger, it is unlikely to obtain this kind of confidence with paper as the source media.

Thus, the business case for P&ID data delivery would be summarized as follows:

- **AS-IS Processes** - P&IDs are too difficult and time-consuming to update and distribute when maintained on paper or vellum. Several non-value-added practices result, e.g., maintaining private copies locally with hand-sketched updates, failing to inform engineering of changes, and revalidating data by walking through the plant.

- **TO-BE Processes** - P&IDs are obtained from E&C firm and maintained as easy to issue and distribute CAD drawings. Separate walk throughs and other revalidations are eliminated and other benefits accrue.
- **HOW-TO Processes** - Designers are retrained on new CAD software and design practices are re-engineered to eliminate local copies and incorporate changes in P&IDs and distribute them quickly.
- **ROI** (Return On Investment) - Improved quality and timeliness of data, reduced redundant copies, and eliminated offset the increased cost and management complexity of procuring P&IDs from E&C firm in CAD format.

In our P&ID business case, we estimate that digital delivery and electronic maintenance and distribution would save about $900 per drawing in revalidating costs.

5. Conclusions

Initially, we presented a constraint framework that can identify all the root constraints and their associated activities for the engineering, construction, and operation of a petrochemical plant. Second, we demonstrated how the constraint framework leads to functional models of design that can be traced directly to the constraints they address. This avoids some of the problems in basing models on design tasks assigned within phases. Third, we demonstrated how external constraints do, in fact, influence design and how to analyze their influence. Fourth, we discussed some of the data that is produced to document that the constraints have been satisfied. We provided a list of some of the tools that support the creation and maintenance of these data sets. Last, we discussed the business case for 3D design and for digital P&ID delivery.

The effect of the new framework is to show both immediate practical application and to identify some promising areas of research. It shows how constraints seemingly targeting downstream processes have a major impact on engineering and construction activities. These constraints can be tabulated and activities that trace to them can be revisited as the constraints change. Contracting and other work practices, however, must be change to reflect this new life-cycle view of design processes and product data. Understanding that impact is the key to reaching the levels of productivity found in the electronics and other high technology industries.

The perspective of nearly all members of the chemical process industry must change to allow themselves to realize the benefits. E&C firms have to shift from realizing the physical plant to realizing a fully operational facility where the integrity of design, safety, and operational data is maintained. The focus of developers of information technology systems must change to deliver comprehensive, well integrated systems that support the entire life cycle of a petrochemical plant. The commitment of E&C firms and plant owner/operators must change to deliver and maintain high quality long life-cycle product data for plants. Also, the thinking of individual designers, constructors, and plant operators must change to recognize the value of having accurate data and complete all reconciliation steps necessary to assure and preserve the integrity of process plant product data.

Other industries have found by making these changes, greater levels of integration and efficiency will be reached, despite the regulatory and financial burdens endured today. In tomorrow's process plant, highly-knowledgeable operators will oversee greater responsibility, supported by computer-based tools of immense power and ease of use. As such tools become used regularly, the possibilities for even greater support will become clear. A solid commitment is needed to create the change.

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Appendix A - Research Agenda

As a result of the present study, we propose a research agenda. Any attempt to assign a Return On Investment (ROI) to various research topics would have to struggle with the following problems:

- Difficulties in determining which processes will be eliminated, improved, or newly required.
- Difficulties in obtaining accurate data about current or projected costs of certain processes.
- Relating costs for one process to the distant root constraints or intermediate decisions which drive it.

We have provided a small demonstration of estimating ROIs in our business case analysis.

Estimating an AS-IS functional model for the broad spectrum of plant products and processes with full dependency of its root constraint drivers is outside the scope of the present work. Perhaps it might never be fully detailed. Very few studies collecting sufficient data about petrochemical costs from all root sources exist; however, those that do collect such cost estimates usually show them as quite high. For example, a study of the U.S. Petroleum Refining Industry by the National Petroleum Council (1993) concludes that the, "...projected U.S. refining capital expenditures of $37 billion (1990 dollars) in the 1991-2000 period for product quality and stationary source regulatory compliance exceed the total net fixed asset base of U.S. refineries of $31 billion at the start of this period." In addition, the report concluded that, "...about two-thirds of the capital expenditures are projected to be made in the 1991-1995 period. Assuming all operating expenses (including depreciation) are recovered, cash flow generated during the 1991-1995 period is still approximately $25 billion less than the required capital expenditures."

Despite the grim news on investment, the National Petroleum Council concludes that "The U.S. refining industry can, with investment, meet foreseen consumer demand and environmental, health, and safety regulatory requirements. Given the industry's recent low profitability and the uncertainties surrounding future regulations and product demands, it is by no means certain that companies will be willing and able to make the necessary expenditures for all facilities." The study was dated August 30, 1993.

Even more detailed studies relating single root changes, e.g., OMB required Regulatory Impact Analysis, are considered subject to error. For example, OSHA estimated, in its February, 1992, Process Safety Management Rule Regulatory Impact Analysis, that the cost of providing Process Safety Information (**PSI**) to the operator averaged $904 per plant for the first five years. This estimate fails to consider that the documentation in most process plants is so outdated that it is inadequate for PSI and other PSM elements as written. One large chemical plant in Port Arthur, Texas budgeted $20 million to update plant documentation over a three year period and had already spent $6 million by the end of the first year [PSM FORUM, Oct 93, Beaumont, TX]. Clearly, the legacy data conversion costs required before compliant processes can start are much higher in cost.

Thus, we present this research agenda with only approximate savings estimates.

A.1 - Better Contract Interfaces
New forms and methods are needed for the interface between the enterprise and agents to whom responsibilities are delegated, particularly in engineering and construction phases. As we have shown, design and construction functions are not just responsible for realizing the plant: They realizing a self-documenting entity complying with multiple root constraints. These root constraints must be visible and controllable through the various technical and management vehicles defined in the contractual relationship.

Research Objectives	Typical topics could include: • Improved Guidance to Owner/operator firms in writing contracts for engineering services and construction. Guidance should include recommended contract language, management interfaces, and improved data, procedural, and certification deliverables. Guidance should also show underlying rationale for each recommendation for easier maintenance. Many E&C firms stay silent on Owner/operator omissions in contracts because their inclusion later means extra fees. • Improved management techniques for E&C contracts involving high traceability to root constraints. Traditionally, E&C firms do not look beyond the contract document for the requirements to be met by the design of a process plant. This is no longer adequate for plants where full regulatory burden cannot be known before design decisions are made. Such additional constraints cannot be deemed "customer changes" each time they are identified.
Processes Affected	Improved processes include: • Reduction in contract management activities. • Reduction or elimination of contract exceptions and changes negations and extra fees. • Reduction in processes to cross-check and aggregate management reports for comparison to high-level goals.
Estimated Savings	Typical engineering cost of changes in the petrochemical industry range from 5-10%. On some nuclear power plant projects, the cost of changes to facilities are much greater. If the cost of changes were reduced by 2½% (i.e.: 8% to 5½%), the resulting savings on a $100 million plant would be $2½ million. If NPC figures of $37 billion are correct for the 1991-2000 decade, reduced engineering change costs could save nearly $1 billion ($925 million).

A.2 - New Forms and Formats for Data	
E&C firms must not only deliver self-documenting compliance operating systems, but their own processes and work products are subject to the same requirements. The document-oriented data and delivery formats structured by such initiatives as CALS (Phase I), will not be adequate to deliver maintainable databases, workflows, certifications and other data and management systems.	
Research Objectives	Typical topics could include: • **System** - independent representations of highly traceable products and processes. Data sets, work processes and relationships intended to meet certain constraints must be supported by representations that document their compliance. The new data structures in these representation must be delivered to clients in formats permitting integration with their own systems. Such new data structures could include: traceable requirements, integrity relationships, audit trails, data dictionaries, and work procedures. • **Specialized tools** for supporting highly traceable products and processes. When products are created, processes are performed, and integrity of relationships maintained, specialized tools will be needed to manage these events and create proper documentation.
Processes Affected	Although design and construction will be burdened with these new requirements, the savings will be in downstream operations, maintenance, regulatory filings/audits, etc. Affected processes include: • Construction of databases for operations, maintenance, and compliance purposes. • Maintenance of data showing proper data, processes, and relationships.

Estimated Savings	OSHA estimated annual compliance costs for its rule alone would be $888.7 million per year for the first five years, dropping to $405 million per year afterward. (Many people in the industry say that true cost could run ten times that figure as the NPC figures indicate). If these annual compliance costs could be reduced by approximately 5% from improved tools and data delivery from design and construction work, or from maintenance and other capital improvements, the savings would be $44 million per year, falling to $20 million.

A.3 - Reverse Engineering & Recapture Issues	
As previously mentioned, a dramatic program of legacy data capture and reverse engineering is currently underway to prepare for compliance with certain regulatory requirements. A large plant can spend up to $20 million to update documentation, and its level of utility for compliance purposes is still largely unknown. Many plant managers have little or no unbiased guidance on optimum levels of conversion for different types of plant documentation and little help in budgeting or planning work to maintain its value.	
Research Objectives	Typical topics could include: • Survey of process plant practice in legacy data conversion. Such a survey would show the current practice for conversion, which documents are considered a priority, and create insight into prioritization rationale. • Prioritization guidance for legacy data conversion. Some documents are more timely than others and current maintenance practices must be integrated with conversion schedules. • Levels of Conversion. This topic would benefit from other representation research, in guiding the selection of the optimal final form for legacy data. This would including how to impose any required relationships or other specialized data structures in the converted data.
Processes Affected	• Scanning, raster-vector conversion, QA/QC and other, one-time, conversion processes. • Maintaining and utilizing processes, which benefit if the data is in proper form.

Estimated Savings	Presuming the $20 million figure per large plant is correct and taking OSHA's estimate of 132 large chemical manufacturing plants (SIC 516), then that industry alone accounts for $2.6 billion in data updating and conversion costs from the one rule. If 10% of this conversion costs could be saved through better guidance and direction, it would save $260 million is SIC 516 alone. Even more savings are possible, when considering increased efficiencies in operations, maintenance, and compliance documentation.

A.4 Optimal Compliance Representations in Life-cycle Data	
Despite the best efforts of the process industry to computerize its maintenance of plant data, most of it remains highly fragmented and not integrated. Clearly, if coordination and reconciliation processes are to be eliminated or minimized, then redundancy must be reduced to a minimum, while considering the overall effect on operational and maintenance efficiency. Such an optimal representation for plant data could be incorporated into E&C contracts to reduce the complexity of data deliverables and guide deliverable development.	
Research Objectives	Typical topics could include: • Optimal distribution of plant data for operations, maintenance, and compliance. • New reconciliation and other maintenance procedures needed to sustain such configurations.
Processes Affected	• E&C data collection, database design, and other activities related to operations, maintenance, and compliance. • Operations, maintenance and compliance processes.
Estimated Savings	Presuming the $37 billion in capital improvements is correct, then a 1% savings might be envisioned from better data management throughout the plant life cycles. This represents a $370 million savings through increased efficiencies in operations, maintenance, and compliance activities.

Appendix B - Key Words or Phrases

OSHA 1910.119
Mechanical Integrity Section J

Rule Type	OSHA 1910.119 Section J Rule Language
Scope	(1) *Application.* Paragraphs (j)(2) through (j)(6) of this section apply to the following process equipment: (i) Pressure vessels and storage tanks; (ii) Piping systems (including piping components such as valves); (iii) Relief and vent systems and devices; (iv) Emergency shutdown systems; (v) Controls (including monitoring devices and sensors, alarms, and interlocks) and, (vi) Pumps.
Product	(2) *Written procedures.* The employer shall establish and implement written procedures to maintain the on-going integrity of process equipment.
Process	(3) Training for process maintenance activities. The employer shall train each employee involved in maintaining the on-going integrity of process equipment in an overview of that process and its hazards and in the procedures applicable to the employee's job tasks to assure that the employee can perform the job tasks in a safe manner.
	(4) *Inspection and testing.*

Process	(i) Inspections and tests <u>shall be performed</u> on process equipment.
Relationship	(ii) Inspection and testing procedures <u>shall follow</u> recognized and generally accepted good engineering practices.
Relationship	(iii) The frequency of inspections and tests of process equipment <u>shall be consistent</u> with applicable manufacturers' recommendations and good engineering practices, and more frequently if determined to be necessary by prior operating experience.
Process Product	(iv) The employer <u>shall document</u> each inspection and test that has been performed on process equipment. The <u>documentation shall identify</u> the date of the inspection or test, the name of the person who performed the inspection or test, the serial number or other identifier of the equipment on which the inspection or test was performed, a description of the inspection or test performed, and the results of the inspection or test.
Process Relationship	(5) *Equipment deficiencies.* The employer <u>shall correct deficiencies</u> in equipment that are outside acceptable limits (<u>defined by</u> the process safety information in paragraph (d) of this section) before further use or in a safe and timely manner when necessary means are taken to assure safe operation.
	(6) *Quality assurance.*
Relationship	(i) In the construction of new plants and equipment, the employer <u>shall assure</u> that equipment as it is fabricated <u>is suitable</u> for the process application for which they will be used.

Process Relationship	(ii)	Appropriate checks and inspections shall be performed to assure that equipment is installed properly and consistent with design specifications and the manufacturer's instructions.
Relationship	(iii)	The employer shall assure that maintenance materials, spare parts and equipment are suitable for the process application for which they will be used.

Appendix C - Example of OSHA Citation Language

Type of Violation . . . . Serious

Date by which Violation must be abated 6/20/90

Penalty $600.00

Rule Type	Citation Language
	Section 5 (a) (1) ...increased likelihood of catastrophic failure of improperly and inadequately maintained pressure vessels. The employer failed to establish, properly implement and manage an effective program of pressure vessels safety including maintenance inspection rating repair alteration and/or replacement. In addition, appropriate records necessary for informed decision making documenting pressure vessels and power piping actual conditions were not prepared, retained, nor made available for inspection. Employees working in the Process Plant were exposed to these hazards for the Amino Heat Exchanger, State Registration #U0180879. A feasible and useful method of correcting these hazards related to pressure vessel and piping rupture and failure is to establish and properly implement an effective program including maintenance inspection rating repair and alteration and/or replacement of pressure vessels piping and their associated safety devices. Such a program must include the following elements as a minimum:

Relationship Not Maintained	1.	Ensure that determination of probable corrosion rate and specification of maximum period between inspections was performed in accordance with the 1989 ASME Boiler & Pressure Vessel Code and 1989 ANSI/National Board Inspection Code sections U-105 and U-106.
Missing Data	2.	Install a name plate that has characters that are readable on the heat exchanger.
Data Incorrect or Missing	3.	Provide markings on the safety relief device to indicate: a Name of manufacturer b Manufacturer design or type number c Size set pressure and certified capacity d year built e ASME symbol

Type of Violation . . . . Serious

Date by which Violation must be abated 6/20/90

Penalty 800.00

Rule Type	Citation Language
(Design) Work Processes	Section 5 (a) (1) ...employees were exposed to severe burns, concussion, multiple traumatic injuries, and/or death from fire/explosion due to: a Not enclosing interior stairway of the process building and installing fire doors. b Not providing drainage to direct flammable and combustible liquid leakage of kettles/mix tanks and fire protection water to a safe location. c Not installing a high temperature limit switch on all closed reactors. d Not bonding containers of flammable liquid when transferring from or to another container.
(Design) Work Processes	Among other methods, one feasible and acceptable abatement method to correct this hazard is to comply with National Fire Protection Association Standards for the Manufacture of Organic Coatings NFPA 35 1987 edition and : a Enclosed stairway with fire resistant material and install fire doors. b Install drainage for kettle/mix tank liquid leakage in the process building c Install a high temperature limit switch on all closed reactors. d Install bonding cable for transfer of resin in portable 5 gallon container from kettles/mix tanks.

Type of Violation .... Serious

Date by which Violation must be abated 6/20/90

Penalty 800.00

Rule Type	Citation Language
	....Section 5 (a) (1) of the Occupational Safety and Health Act of 1970: The employer did not furnish employment and a place of employment which were free from recognized hazards that were causing or likely to cause death or serious physical harm to employees in that employees were exposed to severe burns, concussion, multiple traumatic injuries, and/or death from fire/explosions due to the lack of inerting gas or to the presence of oxidants when solvents are added to process. There were no instruments to indicate the oxidant contents nor were there suitable alarms to signal abnormal operation of the system such as loss of inerting gas or the presence of oxygen in the manufacture of alkyd amino silicone polyester and VT modified resins in the Process Building.
(Design) Work Processes	Among other methods one feasible and acceptable abatement method to correct this hazard is to comply with National Fire Protection Association Standard on Explosion Prevention Systems, NFPA 69, 1986 edition section 2-7 and install: a Instrumentation to ensure that desire oxidant concentration is achieved in the kettle/mix tanks: b An alarm that would indicate abnormal operating condition of the system such as loss of inert gas entry of oxygen into the kettle/mix tanks.

Type of Violation .... Serious

Date by which Violation must be abated 6/20/90

Penalty $800.00

Rule Type	Citation Language
	Section 5 (a) (1) of the Occupational Safety And Health Act of 1970: The employer did not furnish employment and a place of employment which were free from recognized hazards that were causing or likely to cause death of serious physical harm to employees in that employees were exposed to severe burns concussions multiple traumatic injuries and/or death from fire and explosion due to loss of containment and or inadvertent atmospheric release of hot flammable volatile mixtures from process kettles and mix tanks and process kettles which were cleaned with acids and caustic and the failure to determine acceptable corrosion loss in mix tanks and process kettles in the Process Building.

(Design Inspection) Work Processes	Among other methods one feasible and acceptable abatement method to correct this hazard is to establish proper controls over the work being performed that will include but not necessarily be limited to the following: 1 Determine the extent of caustic embrittlement and corrosion in mixing tanks and reactor vessels by the use of nondestructive testing by a qualified inspector in accordance with the American Society of Nondestructive Testing Recommended Practice No SNT-TC-1A. 2 Determine acceptable corrosion allowance loss in mixing tank and reactor vessels with the approval of a registered professional engineer 3 Implement a mixing tank/reaction vessel inspection program with the approval of a registered professional engineer. 4 Implement a mixing tank/reaction vessels cleaning program with detail procedures approved by a registered professional engineer.

Appendix D - Example of Framework IDEF0 Model of Process Plant Design

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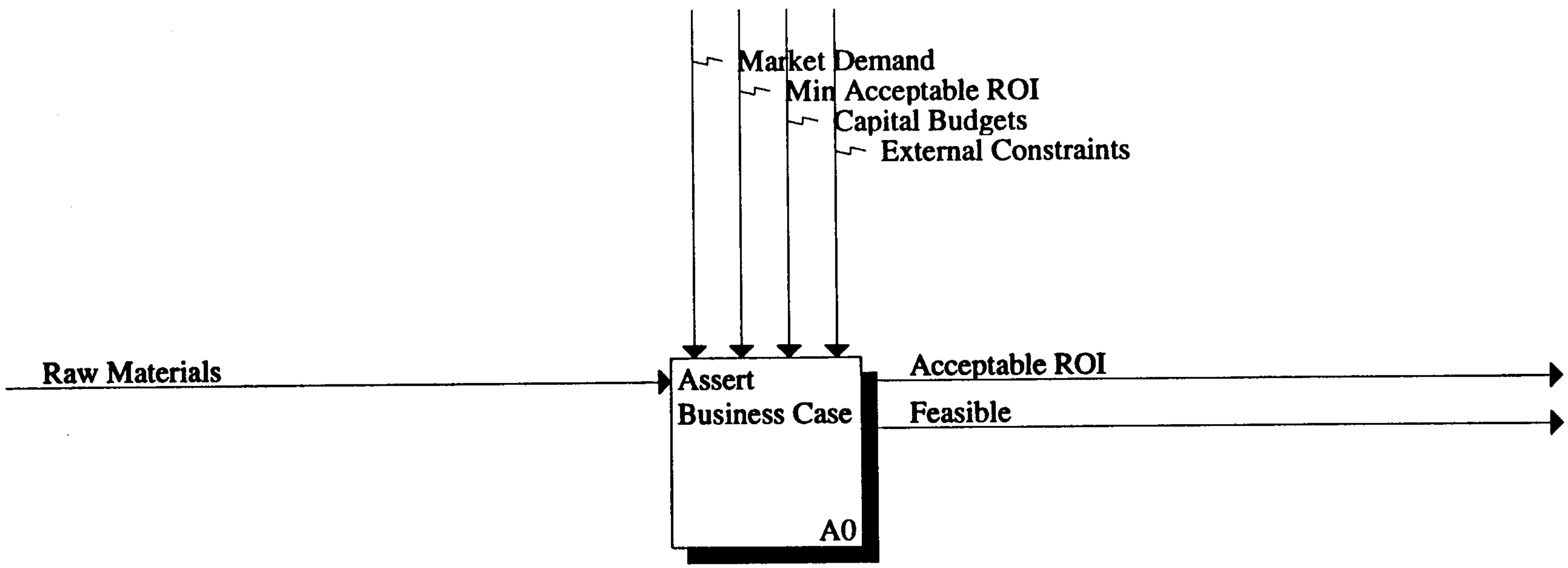

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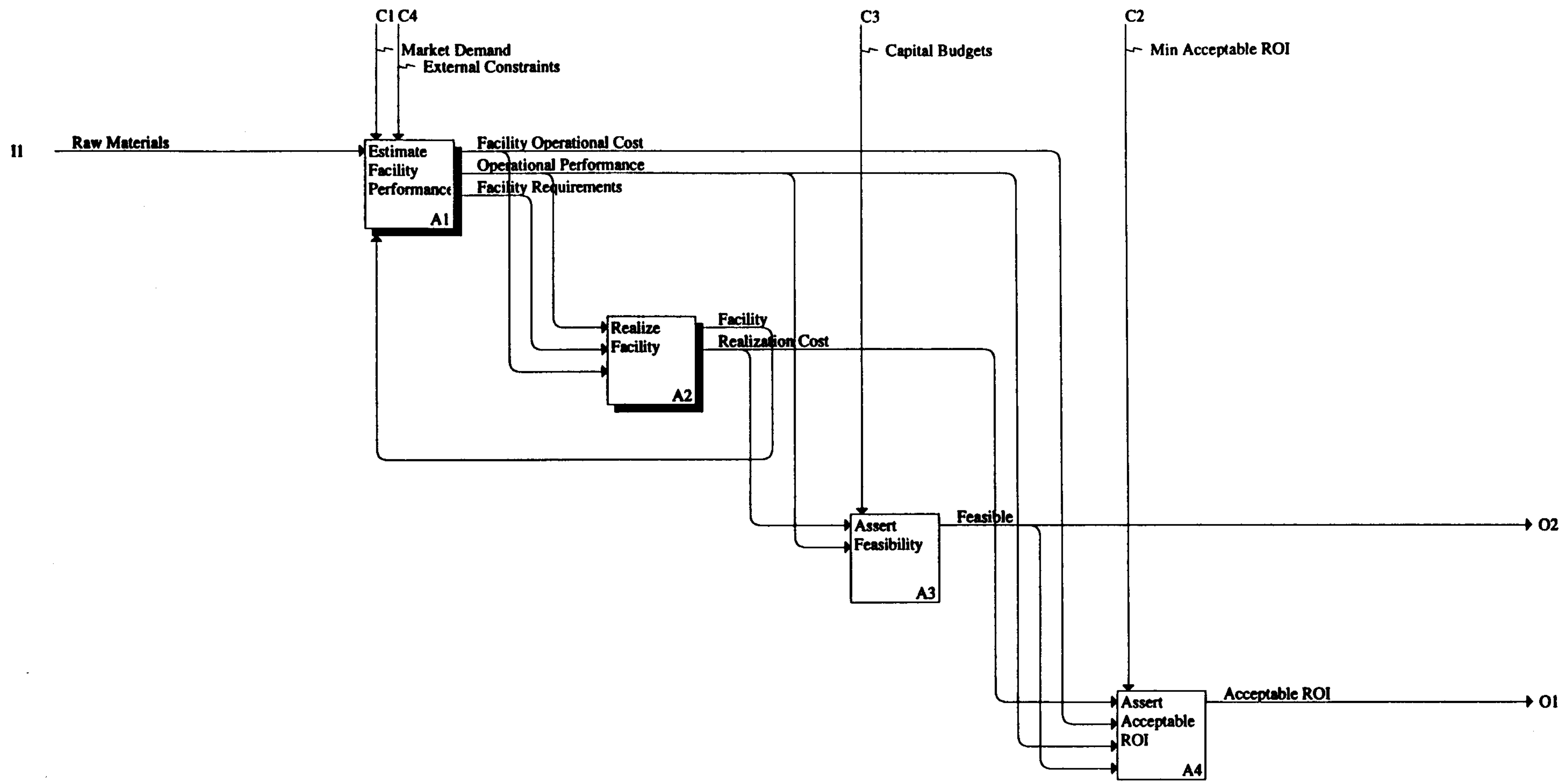

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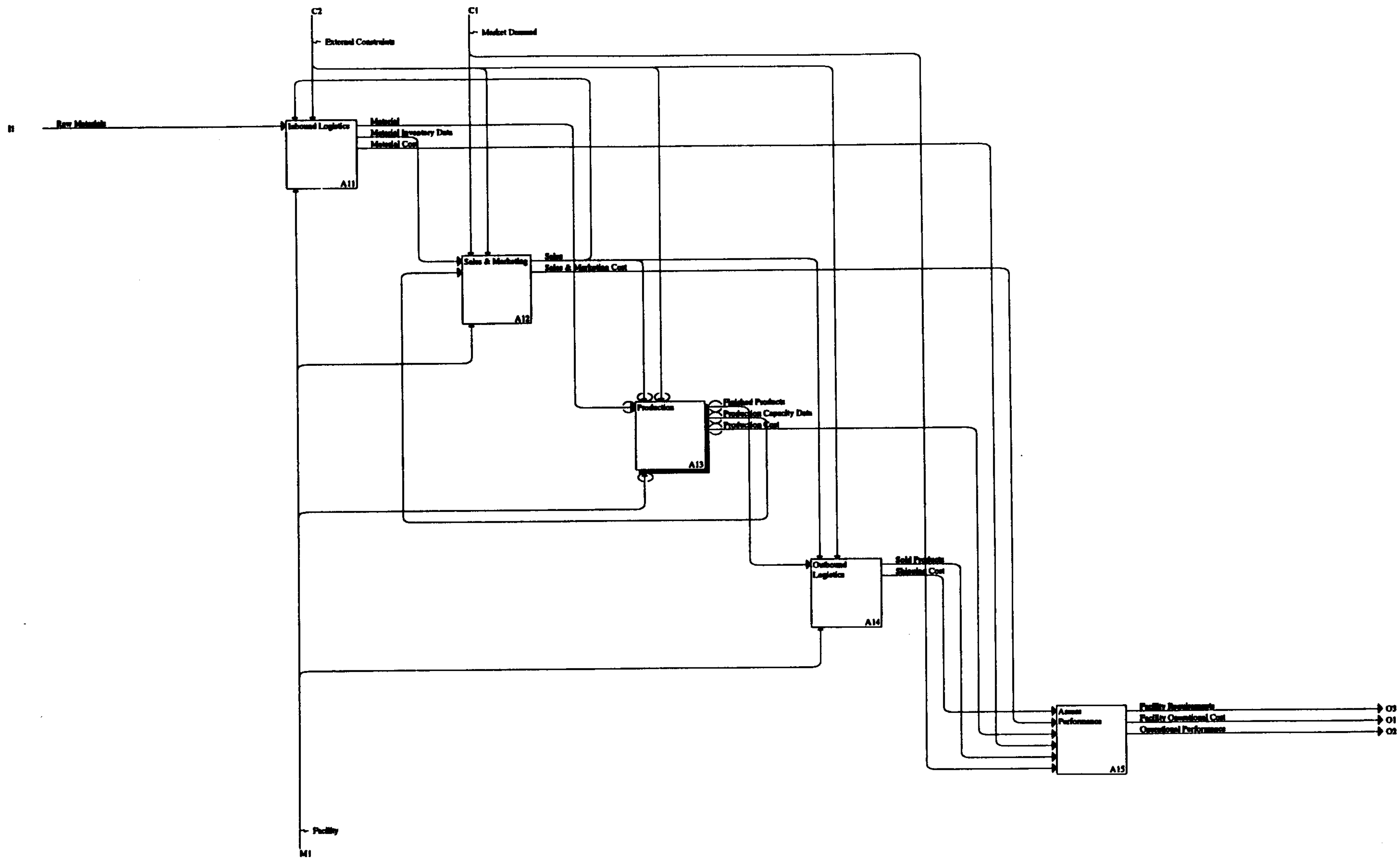

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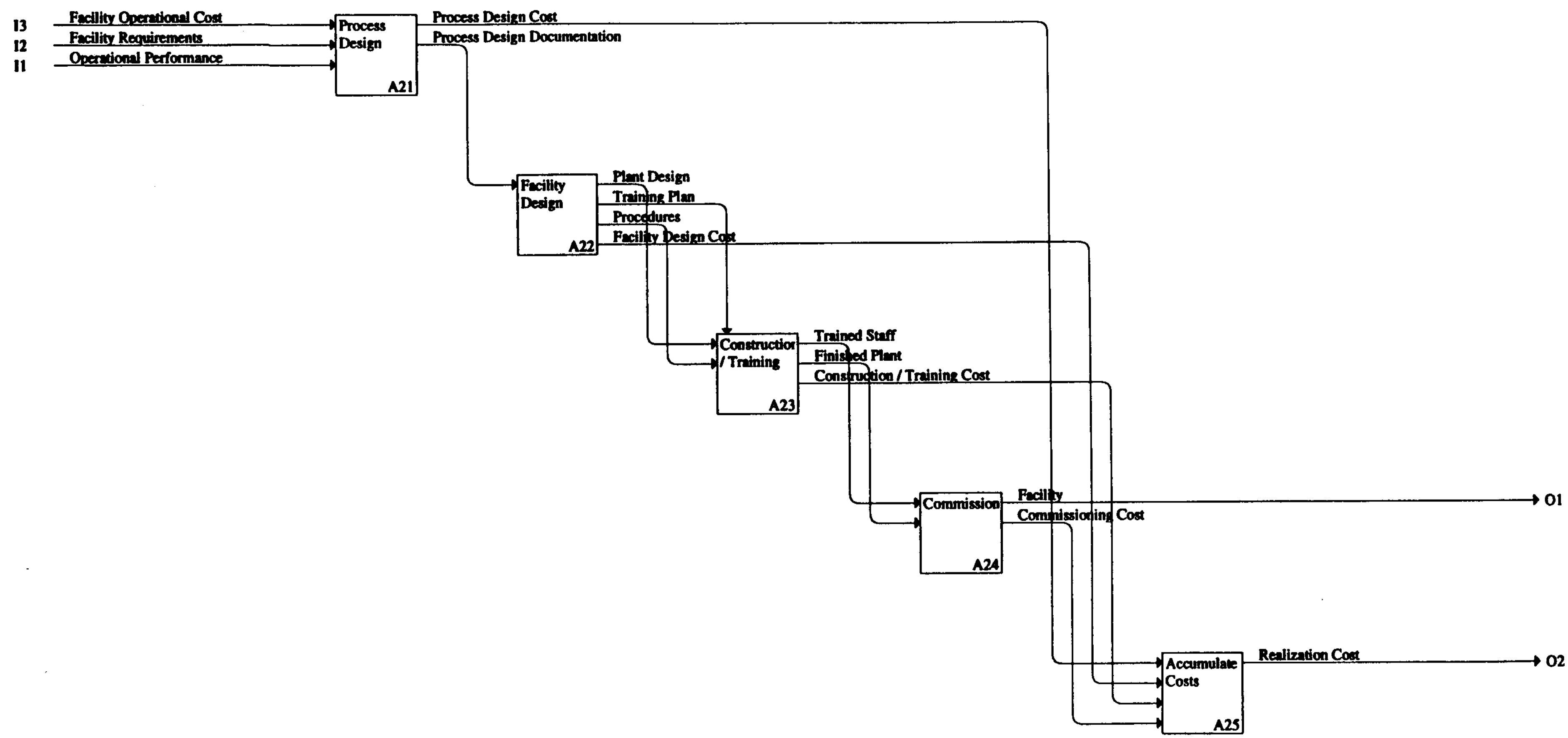

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	Project:	Rev: 0		Draft			
				Recommended			
	Notes: 1 2 3 4 5 6 7 8 9 10	Time: 21:22:21		Publication			

Operate
Process

A131

Node: A13 / C5	Title: Production	Number: Pg 9

Appendix E - Glossary

AIChE	American Institute of Chemical Engineers
ANSI	American National Standards Institute
AP	Application Protocol
API	American Petroleum Institute
ASME	American Society of Mechanical Engineers
BOM	Bill of Material
CAD	Computer Aided Drafting and/or Computer Aided Design
CAE	Computer Aided Engineering
CAM	Computer Aided Manufacturing
CAX	Computer Aided X (Design, Manufacturing, Engineering)
CIC	Computer Integrated Construction Group at NIST
CFI	Client Furnished Information
CMA	Chemical Manufactures Association
DoT	Department of Transportation
E&C	Engineering & Construction
EDI	Electronic Data Interchange
EDMS	Engineering Data Management System
EPA	Environmental Protection Agency
FERC	Federal Energy Regulatory Commission
HVAC	Heating, Ventilation, and Air Conditioning
IDEF0	Integrated Definition Method 0 - Functional Process Capture
IDEF6	Integrated Definition Method 6 - Rationale Capture
IICE	Information Integration for Concurrent Engineering
IT	Information Technology
MOC	Management of Change System
MSDS	Material Safety Data Sheet

NIST	National Institute of Standards and Technology
OMB	Office of Management and Budget
OSHA	Occupational Safety and Health Administration
P&ID	Piping & Instrumentation Diagram
PDXI	Petroleum Data Exchange Institute
PetroSEP	Petrochemical Special Emphasis Program
PFD	Process Flow Diagram
PHA	Process Hazards Analysis
PISTEP	Plant Information Interchange Via STEP
PSI	Process Safety Information
PSM	Process Safety Management (OSHA 1910.119) Rule
ROI	Return On Investment
RMP	Risk Management Rule (EPA) Rule
RMS	Requirements Management System
SASE	Standard Analysis, Synthesis, and Expressions System
SEC	Securities Exchange Commission
SOP	Standard Operating Procedures
SOW	Statement of Work
STEP	ISO 10303 (Standard for the Exchange of Product Model Data, or "STEP")